

Status and Issues for Reactor Safety Code Modeling of Future Reactor Designs

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Advanced Simulations: A Critical Tool for Future Nuclear
Fuel Cycles*

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*Karen Vierow, Assistant Professor
School of Nuclear Engineering, Purdue University
Director, Laboratory for Nuclear Heat Transfer Systems*



Laboratory for Nuclear Heat Transfer Systems, Purdue University



Overview of Presentation

- *Analysis Needs Posed by Future Reactor Designs*
- *Challenges for Reactor Safety Codes*
- *Overview of Reactor Safety Code Applications to Future Reactors*
- *Methods for Extending Code Capabilities*
- *Current and Future Issues*
- *Conclusions*

The MELCOR work discussed herein is performed in collaboration with, and under sponsorship of, Sandia National Laboratories (Randy Gauntt, Sal Rodriguez)



Analysis Needs Posed by Future Reactor Designs

- *Objectives for Future Reactors*

Electricity generation

+ hydrogen production

+ desalination

+ oil extraction (with steam) and oil conversion to a useful product (with hydrogen produced by nuclear)

+ other applications

- *Future reactor designs include:*

- High-temperature gas-cooled reactors*

- The Advanced High Temperature Reactor (AHTR)*

- Supercritical reactors*

- Liquid metal fast reactors*



Analysis Needs Posed by Future Reactor Designs

- *Analysis Needs*
 - *Design tools* for the reactor and associated components and processes
 - *Predictive capabilities for ensuring safety* of future reactor designs
 - *Evaluation tools for design certification and licensing processes*
 - *Analysis results must present a strong safety case with a high level of proof for reactor licensing*



Challenges for Reactor Safety Codes

- *A current focus is to modify LWR safety codes*
- *Future reactors may employ:*
 - *New fuels*
 - *Different geometries*
 - *Materials not in LWR cores*
 - *New safety features*
 - *Different coolants*
 - *Gases, molten salts, liquid metals*
 - *Equations of State must be re-evaluated and/or modified*
 - *Higher temperature operating conditions*
 - *Materials issues*
 - *Increased importance of radiation heat transfer*
 - *Different neutronics characteristics*



Challenges for Reactor Safety Codes

- *Additional challenges*
 - *Events relevant to high-temperature gas-cooled reactors differ from those in LWR's*
 - *DBAs in the PBMR*
 - *Pressurized loss of forced circulation (P-LOFC)*
 - *Depressurized loss of forced circulation (D-LOFC)*
 - *D-LOFC with Air Ingress*
 - *P-LOFC plus Anticipated Transient Without Scram (ATWS)*
 - *D-LOFC with ATWS*
 - *New severe accident models are needed for phenomena peculiar to the future reactors*



Overview of Reactor Safety Codes Applied to Future Reactor Analysis

- *Overview of Reactor Safety Codes*
 - *Focus herein on US codes currently being developed for future reactor analysis*
 - *Gas-cooled reactor codes*
 - *GRSAC*
 - *LWR codes*
 - *ATHENA + FLUENT + CONTAIN*
 - *MAAP4*
 - *MANTRA*
 - *MELCOR*
 - *RELAP5-3D*



Overview of Reactor Safety Codes

- *Existing code for gas-cooled reactors*
 - *GRSAC (Ball, 2002)*
 - *Graphite Reactor Severe Accident Code*
 - *3-D core thermal hydraulics (~3000 nodes)*
 - *Optional neutronics (point kinetics) for ATWS accidents*
 - *Several severe accident models*
 - *Adaptations to GT-MHR & PBMR in progress*
 - *Models for rapid depressurization events said to be under development*
 - *Brayton cycle balance of plant not modeled*



Overview of Reactor Safety Codes

- *LWR Codes*
 - *MELCOR (SNL, Purdue, 2005)*
 - *A flexible code due to MELCOR's control volume-flow path approach and control function capabilities*
 - *Modeling techniques available for spherical fuel and gas coolant without code modification*
 - *Models for pressure drop in packed bed, heat transfer in pebble bed*
 - *Air/graphite oxidation models being implemented*
 - *Addition of models for simulation of the entire hydrogen production plant in progress*
 - *Compressor, heat exchanger, thermochemical reactions*
 - *Generalization of the working fluid and EOS*
 - *Other coolants such as sodium for fast reactors*



Overview of Reactor Safety Codes

- *LWR Codes*
 - *ATHENA (Johnsen, INL, 2004)*
 - *A version of RELAP5 developed for NRC and DOE, funded by DOE*
 - *Model for 1-D spherical conduction*
 - *Models for forced convection and pressure drop in pebble bed*
 - *Multidimensional hydrodynamic models*
 - *NESTLE multidimensional nodal kinetics model*
 - *Graphite pebble oxidation in air and steam*
 - *Coupled to CONTAIN and FLUENT for detailed internal flow analysis*

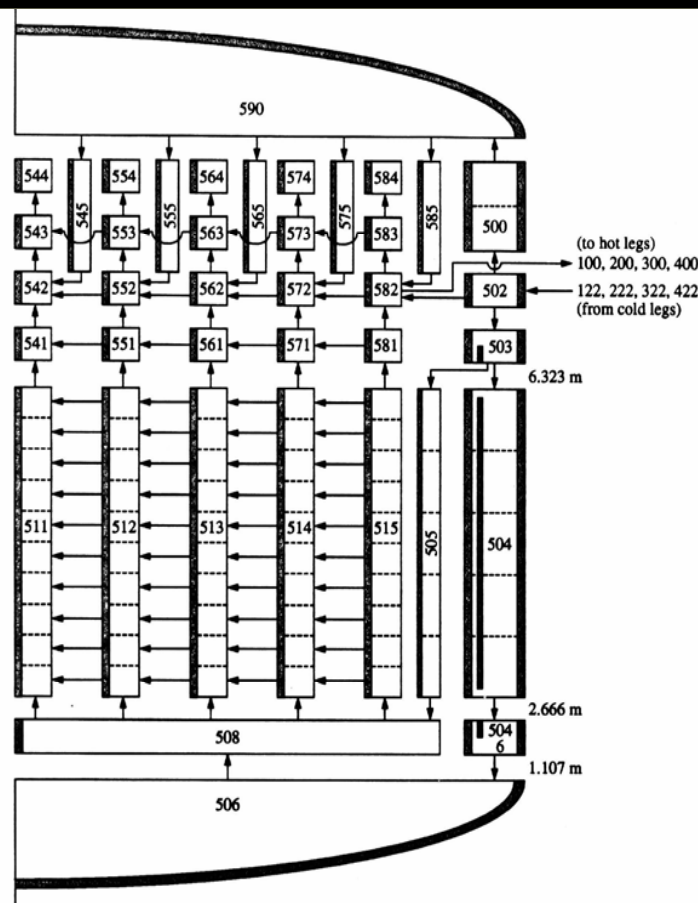


Overview of Reactor Safety Codes

- *LWR Codes*
 - *RELAP5-3D*
 - *Supported through NERI program (Davis et al., 2005)*
 - *SCDAP/RELAP5 model for pressure drop across packed beds (Ergun equation)*
 - *Molecular diffusion model for analysis of VHTR's currently being validated*
 - *Compressor model under development (Johnsen, 2004)*
 - *Current applications include VHTR, supercritical reactor, gas-cooled fast reactor (Johnsen, 2004)*

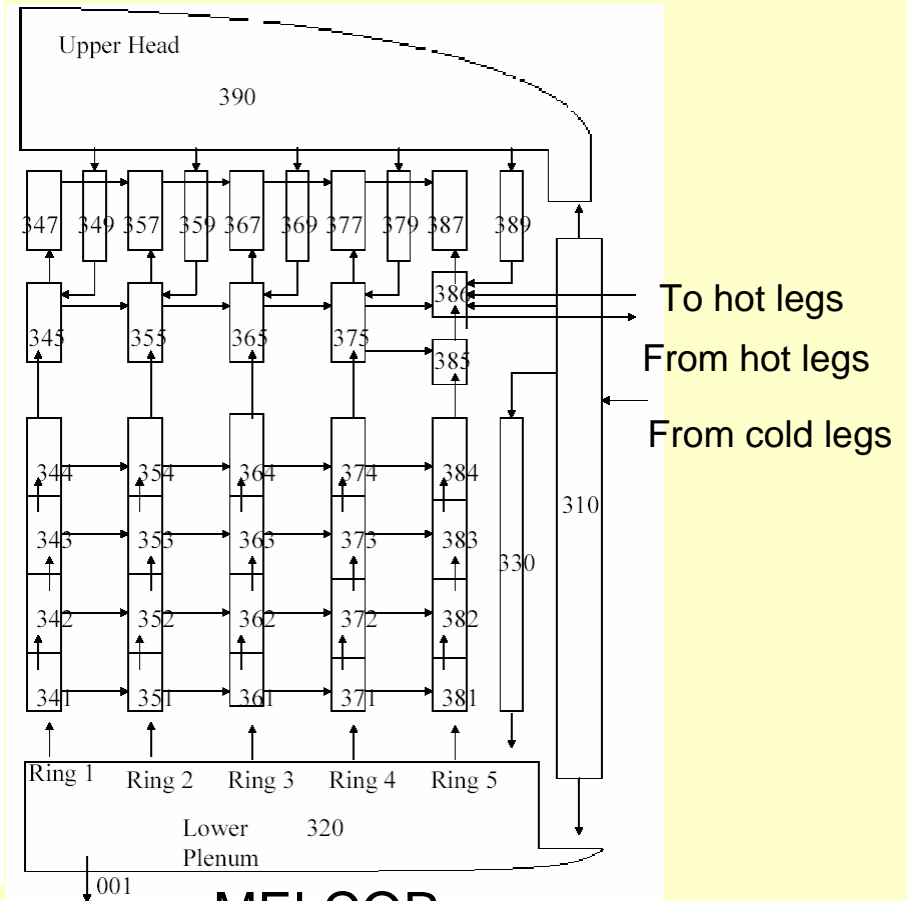


Overview of Reactor Safety Codes



SCDAP/RELAP5

Ref: L. Ward,
US NRC

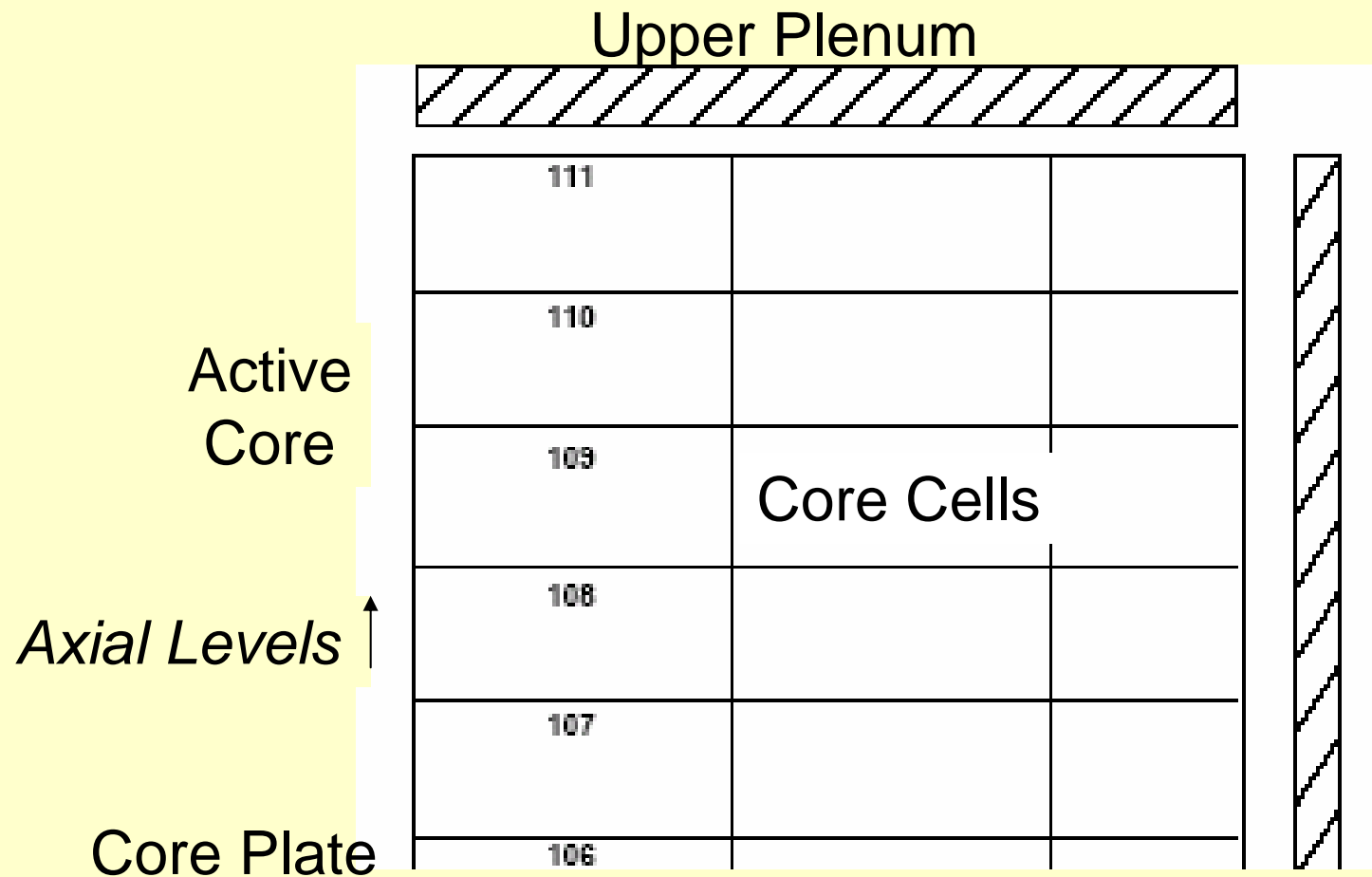


MELCOR

Zion PWR Vessel Nodalization



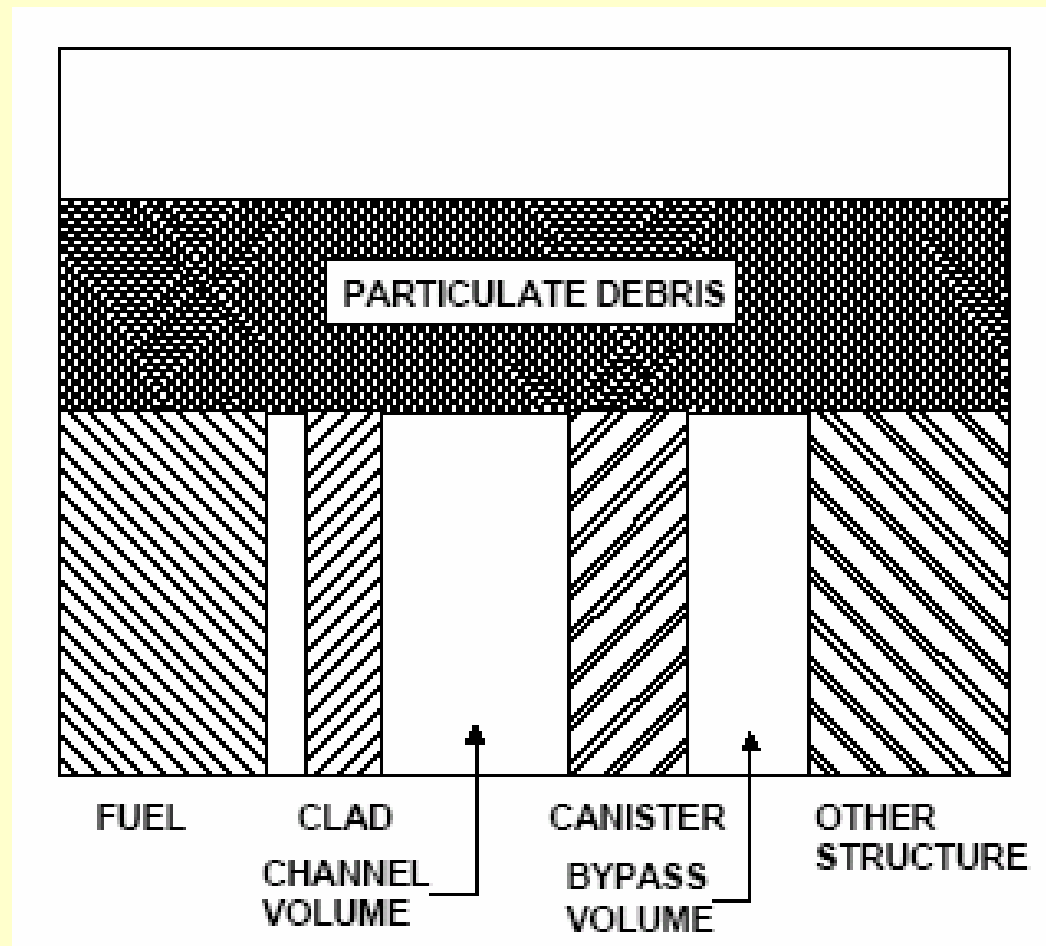
Overview of Reactor Safety Codes



Radial Rings →
MELCOR Modeling of Degraded Core
Laboratory for Nuclear Heat Transfer Systems, Purdue University



Overview of Reactor Safety Codes



MELCOR Modeling of Degraded Core

Laboratory for Nuclear Heat Transfer Systems, Purdue University



Overview of Reactor Safety Codes

- *Core Degradation*
 - *Each code uses different components and models to analyze the degraded LWR core*

<i>LWR Degraded Core Components Modeled</i>		
<i>MELCOR</i>	<i>SCDAP/RELAP5</i>	<i>MAAP4</i>
<ul style="list-style-type: none">• <i>particulate debris</i>• <i>particulate debris in the BWR bypass</i>• <i>molten pool model</i>	<ul style="list-style-type: none">• <i>porous debris</i>• <i>nonporous debris</i>• <i>molten or frozen ceramic pool</i>	<ul style="list-style-type: none">• <i>lumped component of fuel, clad, control rod/blade, fuel all at the same temperature</i>• <i>water</i>

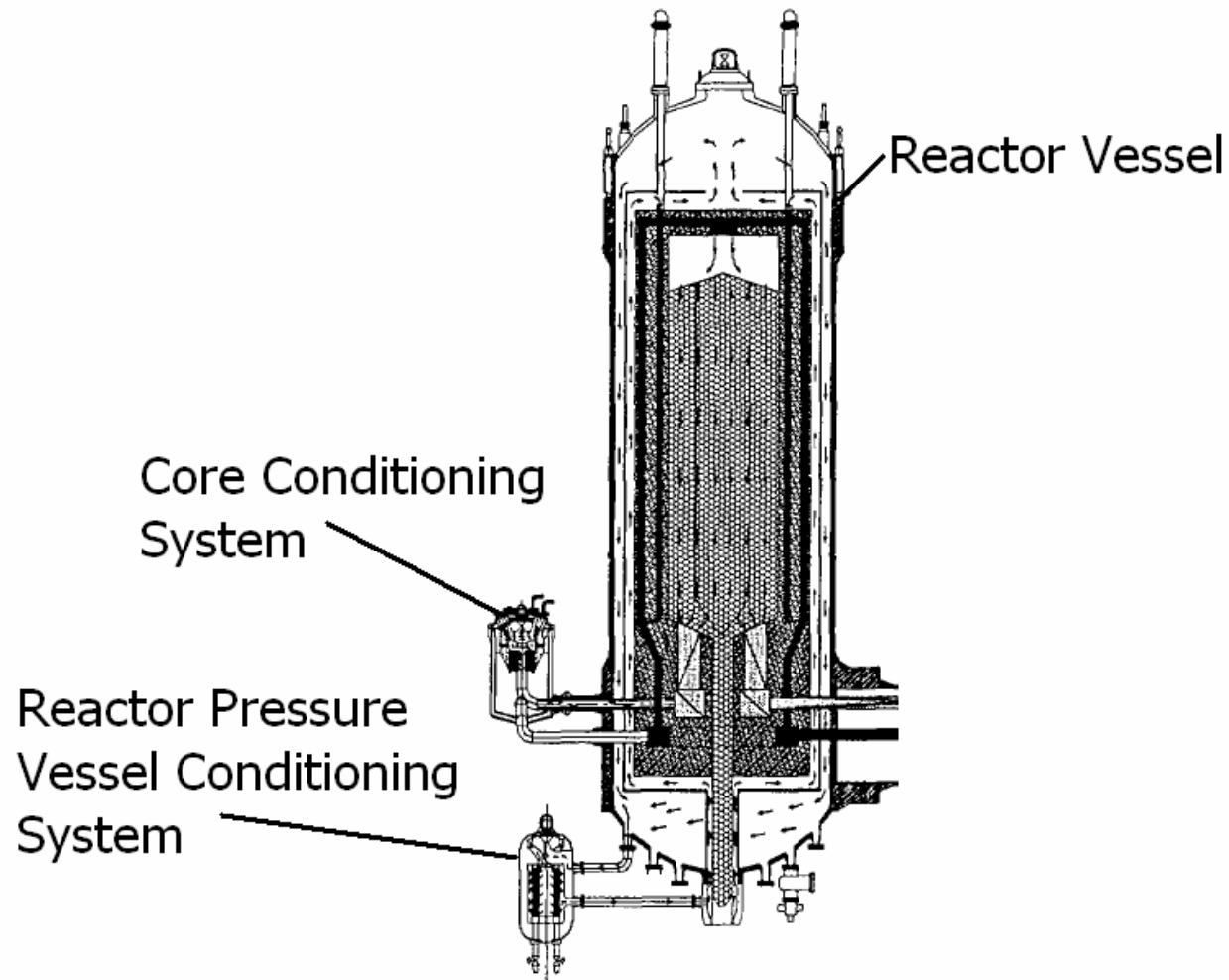


Methods for Extending Code Capabilities

- *Current effort with MELCOR*
 - *Collaboration between Sandia National Labs and Purdue University*
 - *Current focus on PBMR*
 - *Will model VHTR when design data is available*
 - *Currently being modified for analysis of Brayton cycle*
 - *Modifying for integrated simulation of hydrogen plant*
 - *Planning for expansion to other reactor concepts*



Methods for Extending Code Capabilities



PBMR RPV

Laboratory for Nuclear Heat Transfer Systems, Purdue University



Methods for Extending Code Capabilities

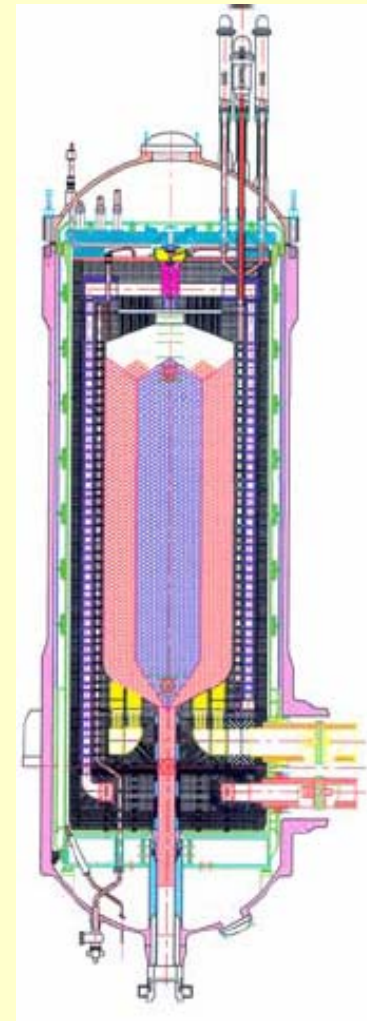
MELCOR PBMR Pebble Bed Modeling

- *After LWR fuel pin collapses, “particulate debris” (PD) forms*
 - *Computationally defined as a packed bed with a user-specified radius and porosity*
- *Particulate debris is used to simulate a packed bed of fuel spheres*
 - *Triggers a flow blockage model that calculates pressure drop using the Ergun equation*
 - *Approximates heat transfer in a packed bed*
 - *Currently using lumped parameter model for the spheres*



Methods for Extending Code Capabilities

- *Major Areas of Coolant Flow in PBMR*
 - *Inlet plenum featuring a colander-like entrance grating*
 - *Pebble bed in core*
 - *Annular bypass surrounding reactor core*
 - *Void region above core which encourages gas mixing*
 - *Helium outlet plenum in a conical shape*



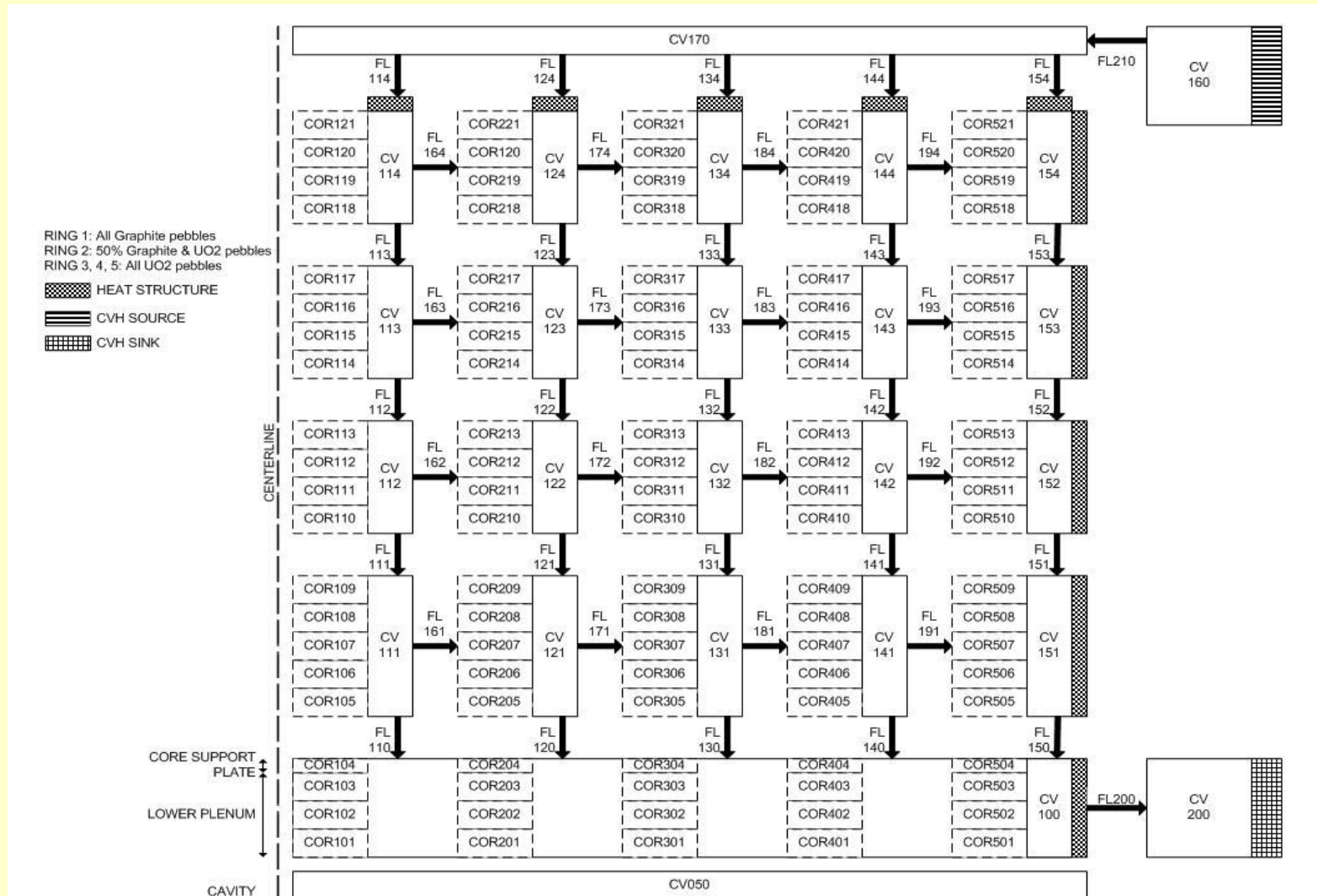
Methods for Extending Code Capabilities

MELCOR PBMR Coolant Flow Modeling

- *Water is the coolant used by default in MELCOR*
 - *Uses a two-phase flow model (pool and atmosphere)*
- *A gaseous coolant may be specified instead of steam/water*
 - *Gas properties embedded in code as formulas, particularly, the ideal gas law*
- *Courant number is not limiting even at high velocities*
 - *Gas velocities > 100 m/s*
 - *Nodalization can be course enough to avoid timestep difficulties yet obtain reasonable simulation*



Methods for Extending Code Capabilities



MELCOR PBMR Nodalization

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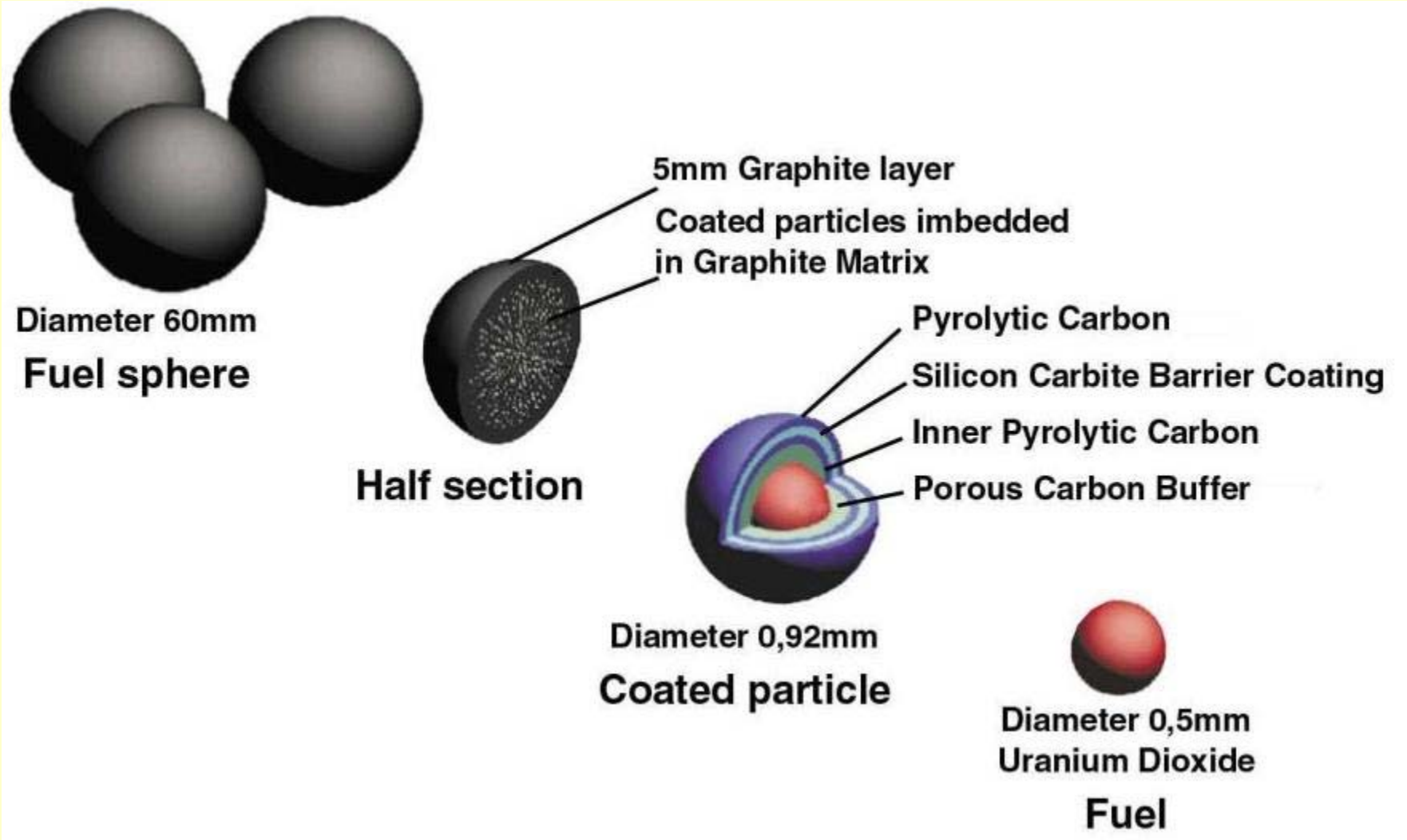


Current and Future Issues

- *Upgrade of the fuel models to accurately represent the new fuel safety features for severe accidents*
- *Spatial change of the pebble packing fraction for PBMR*
 - *Potential for localized hot spots within core*
- *Complicated gas flow patterns*
 - *At the core exit where maximum coolant and structural temperatures may occur*
- *Uncertainties in modeling phenomena we don't have detailed knowledge of*
 - *Severe accident fission product release and transport*
- *Integrated plant simulations*
- *Code validation*



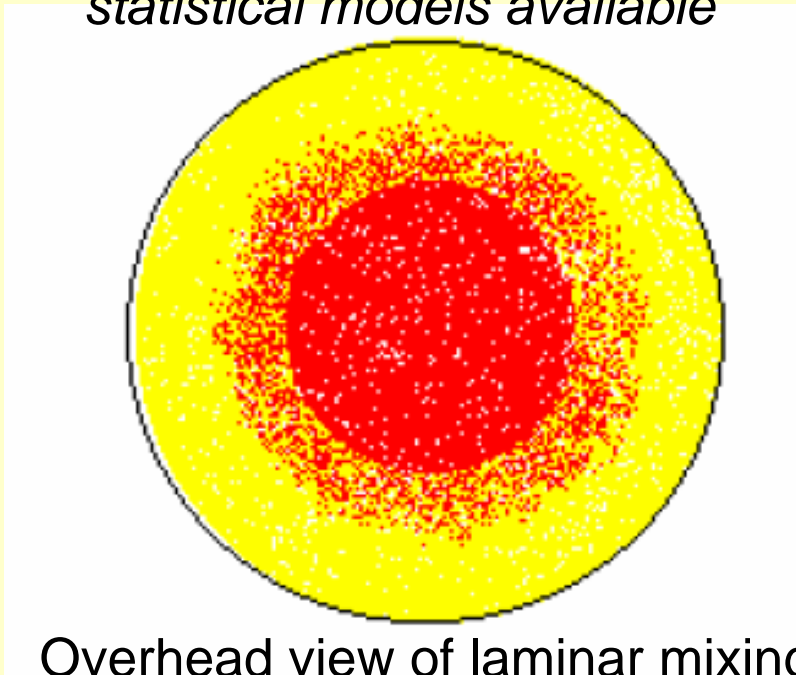
Current and Future Issues: Fuel Modeling



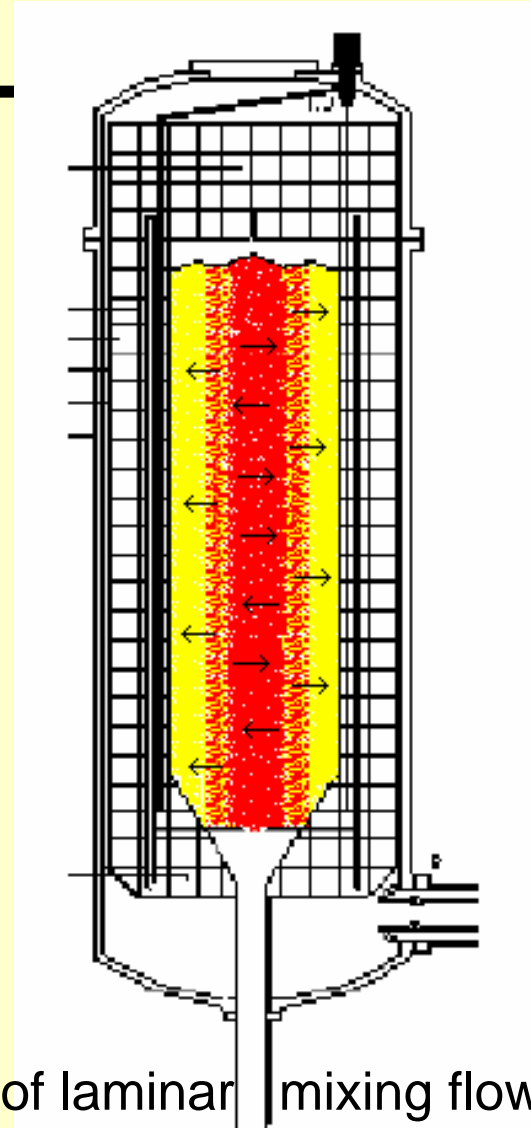
PBMR TRISO Fuel Details

Current and Future Issues: PBMR Pebble Diffusion

- *Pebble configuration in core*
 - *Consider variations in porosity as a function of radial position; some statistical models available*

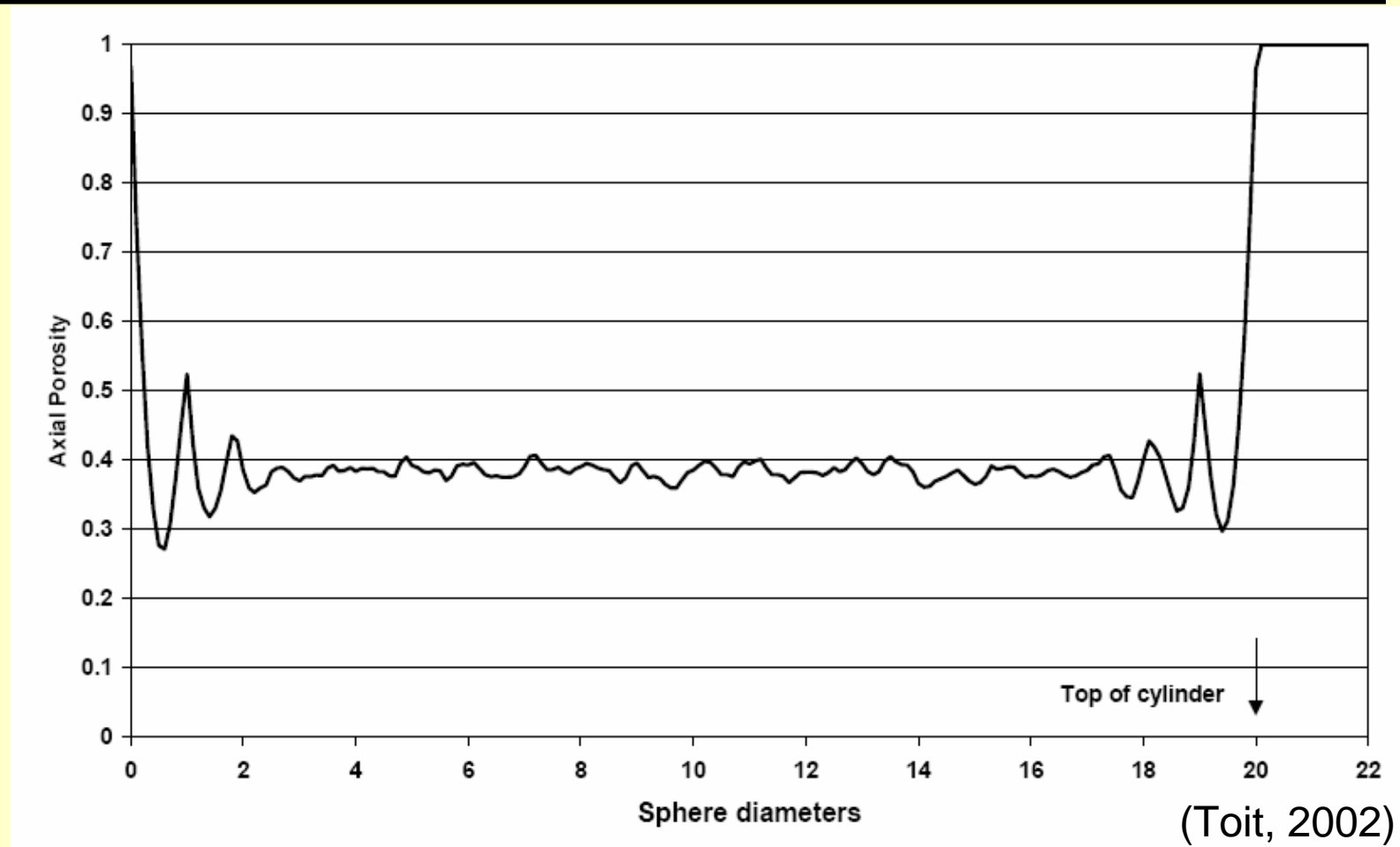


Overhead view of laminar mixing flow



Side view of laminar mixing flow

Current and Future Issues: PBMR Pebble Diffusion

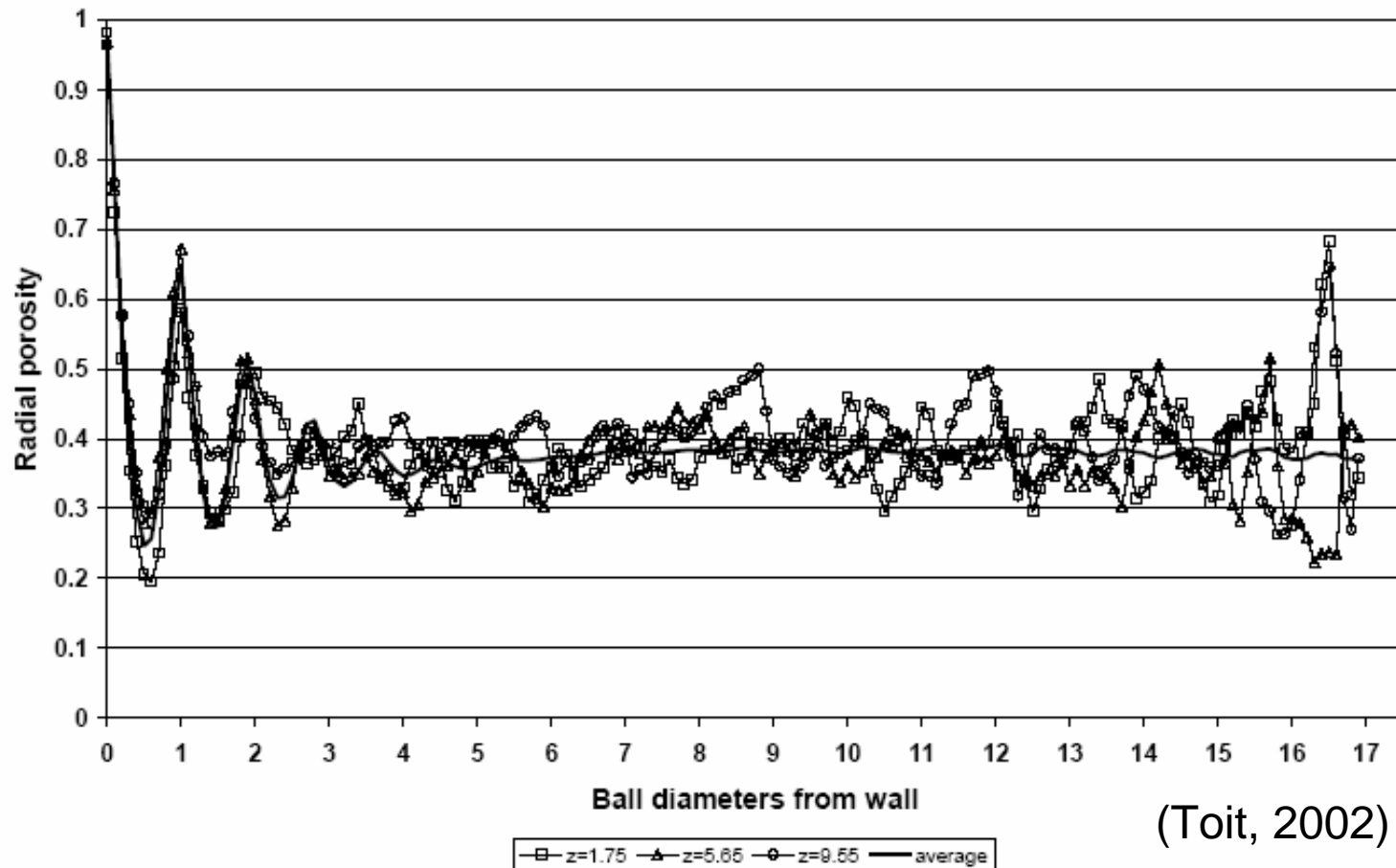


Variation in Axial Core Porosity

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Current and Future Issues: PBMR Pebble Diffusion



Variation in Radial Core Porosity

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Current and Future Issues: Modeling Uncertainties

- *Modeling Uncertainties*
 - *Methods to address uncertainties*
 - *Sensitivity studies (to identify key uncertainties)*
 - *Improvement of code models*
 - *Large number of calculations with samplings of uncertain parameters*



Current and Future Issues: Integrated Plant Simulations

- *Couple reactor models to*
 - *Brayton cycle components*
 - *Thermochemical plants*
 - *Desalination plants*
 - *Etc.*
- *Investigate safety implications of the combined systems*



Current and Future Issues: Model Validation

- *A well-defined strategy is needed*
 - *Use Code Scaling, Applicability and Uncertainty Analysis (CSAU) methodology?*
 - *Are sufficient test data available?*
- *PBMR Model Validation*
 - *Several sources of neutronics data exist*
 - *Several critical facilities provide data for PBMR*
 - *Three actual reactors provide data*
 - *AVR, THTR, HTR-10*
 - *Discussion of the limited availability of thermal hydraulic data ongoing*
 - *Some data exist*
 - *INL is validating gas diffusion models against Hishida's data and natural circulation calculations against NACOK data (Davis, 2005)*



Conclusions

- *New analysis models and techniques are needed for future reactors and associated components and processes.*
- *Fuel models represent key challenges due to new geometries, safety features and operating conditions*
 - *Analysis results must present a strong safety case with a high level of proof for reactor licensing.*
- *Several efforts are ongoing to extend LWR safety code capabilities to Gen IV reactor analysis*
 - *Varying techniques and assumptions are made by different developers*
 - *Collaborations and sharing of information will speed the code development progress*

